IN SITU MONITORING OF LOCAL SEISMICITY

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ABSTRACT An essential element of CTBT IMS monitoring is accurate epicenter locations. Recently, focus is on the IASPEI 1991 travel time tables which are not adequate for global usages due to strong upper mantle velocity variations in many regions. Related problems are network configurations (too few reporting stations) and persistent identification and pickings of secondary phases. For small array records, phase velocities can be estimated via f-k analysis but still differentiations between Pg-, PmP- and Pn-phases and likewise Sn- and Lg-phases remain problematic. In the latter case the issue is whether ray theory is adequate for describing wave propagation in the crustal wave guide.

We are considering two approaches to the above problems; namely i) to analyze existing monitoring performances using NORSAR GBF-bulletin data including use of close-in station records from the Khibiny and ii) event discrimination in W. Norway. The GFB data cover 1999 and the total no of events were 7793 mainly stemming from Kiruna, Sweden (3544), Khibiny, Kola (956) and Zapolarny, Kola (325). To our surprise, there is no strong correlation between event occurrences and time-of-day nor day-of-week. The only exception here is Kiruna with a strong concentration of explosions at midnight hours. By taking first and second order derivatives of spatial histograms (seismicity plot) it is easy to identify the above mining areas particularly through the curvature plot. The events areal coverage for the respective mining areas amount to an aperture about 1° so accuracy is not unreasonable since bulletin production is automated. However, the strongest curvature are found for areas close to specific mine locations so we test this concept on other parts of Fennoscandia like W. Norway in order to locate the many quarries in industrialized areas. Simply, delete events in areas exhibiting small curvature. We would also see if we in this manner may better outline active faults through earthquake occurrences. A close scrutiny of some Khibiny mine explosions comparing epicenter determinations using our new Nansen station records and the listings from the Kola Seismological Center, Apatity gave locations difference close to 30 km in the extreme although epicenter distances were less than 60 km. In other words, travel time tables are not the lone cause of occasionally poor event locations. An alternative to formal epicenter determination procedures is to use waveforms instead of individual P- and S-phases. We have with base in the Nansen station tried a large number of schemes using the covariance matrix based on the 3-component recordings but really have problems in consistently recognizing signals from a specific mine. For W. Norway we used 10 years of manually produced bulletins subjecting these event listings to cluster analysis as well. As for N. Fennoscandia & Kola large land areas are almost void of earthquakes so many hundreds of bulletin events are exclusively explosions. Likewise, in off-shore areas reported events are exclusively earthquakes. However, in the intermediate coastal areas we have mix of earthquakes and explosions in the event population not easily separable by cluster analysis alone. Reason being harbor construction works which may take place at any hour of the day. A confusing aspect of the bulletin event listings is that non-zero focal depth estimates are no proof of an earthquake source.

Both for Fennoscandia & Kola and W. Norway cluster analysis have proved very efficient in isolating space-time stationary source areas areas from which explosion signals dominate in the event listings. Most of these signal sources are besides easily recognizable as such through signal envelope analysis using ANN source discrimination schemes.

Key words: Epicenter location, mine explosions, waveform classifier, Bayes statistics, Khibiny, N. Fennoscandia, Kola, W. Norway .

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OBJECTIVE

A seismic monitoring nuisance is the national network recordings of numerous chemical explosions in many countries. These events are of marginal scientific interest but on the other hand constitute the same processing and analyst loads as in case of earthquake recordings. In the context of the CTBTO/IMS global monitoring system it is highly desirable to eliminate these local explosion recordings to prevent system overloading both on national and IMS networks levels. In case of the IMS this is done by i) requiring at least 3 alpha station/array reports or ii) event magnitude being less than 3.5 units. On local network levels small earthquakes are of prime research interest at least in aseismic countries so the explosion/earthquake discrimination problems persists down to small event magnitudes. Naturally, there has been many and successful local discrimination studies using primarily the Pn/Lg-discriminant (Blandford, 1996; Dowla, 1996; Shapira et al, 1996) but such analysis are seldom integrated in daily processing tasks. An important part of the discrimination problem is that of establishing reliable ground truth data bases which are not always simple in areas where occurring earthquakes (EQs) constitute only a few percent of the event population. The ultimate solution here is to tie EQ occurrence only to those felt and/or those with m_b magnitude exceeding 3.0. Another aspect of explosion identification is the often poor network epicenter locations capabilities producing diffuse seismicity patterns typical of natural EQ occurrence. In any country, use of explosive charges exceeding a few tonne of dynamite is strictly regulated so recordable explosions are confined to very small areas. In this study, we investigate event distribution in Fennoscandia and NW Russia (Kola) as reported by Norsar through their bulletins for the time period Oct, 98 - Oct, 99 based on their generalized beamforming technique for automatic epicenter determination. The Norsar array network as used, comprises the regional arrays Noress (N), Arcess (N), Hagfors (S), Finessa (SF) and the 2 miniarrays Spitsbergen (N) and Apatity (RU). The accuracy of epicenter locations depends both on geometry and no of reporting arrays which here are not quantified in terms of mislocation probabilities. As a complement to the Fennoscandia & Kola study we have also investigated the event distribution in W. Norway. The data used are 10 years of bulletin listings 01/01/90 - 31/12/99. For this area the epicenter locations are far more accurate due a relatively dense local network operated by the University of Bergen and analyst inspections of recordings.

RESEARCH ACCOMPLISHED

BULLETIN SCREENING

We started with the classical approach that is plotting event occurrence as functions of time of day and day of week for the 3 active mining areas Kiruna (S), Khibiny (RU) and Zapolarny (RU) (Fig. 1). It is somewhat surprising that the event occurrence are reasonably flat with exception of Kiruna where midnight explosions dominate. If we subtract the events in the 3 mining areas from the total event population and then fitting a plane to the histogram surface we obtained the probability density function (p.d.f.) $p(x, y, t) \sim 10^{-6}$ km^{-2}year^{-1}. Even for an area of 1000 km^2 the probability for earthquake (EQ) occurrence is extremely small. Similar area and histogram plots for W. Norway are shown in Fig. 5. In this area the event distributions are more complicated as off-shore areas are obviously earthquake prone.

PROBABILITIES OF EARTHQUAKES IN THE EXPLOSION POPULATIONS

In some of our previous studies (Fedorenko et al., 1998; Fedorenko et al., 1999) we restricted our discrimination research to recognize seismic signals (envelopes) from specific mines and quarries. Basic assumption was that signal waveforms were time and spatial stationary which in practice appeared to be valid. However, using quarry blast signals for which exact ground truth information was lacking our recognition scheme become less accurate. In other words, can we quantify the p.d.f. of selecting learning sets correctly from ground truth data bases? We have used the above data set from N. Fennoscandia and Kola for such an experiment. This area is suitable for such experiments since very, very few earthquakes appear to occur here.

As a mean to screen out explosions automatically a Neural Network (NN) scheme may be used. Previously, we have shown that such algorithms when applied to multistation or multicomponent waveform recordings exhibit well defined epicenter location accuracies. Let the function describing it be $A(\varphi, \lambda)$ where φ, λ are latitude and longitude, or $A(x, y)$ with x and y being distances in km. This function shows the relative number of events "passing through" the NN algorithm. If the width of $A(x, y)$ is reasonably small, the explosion recognition may be very reliable just using their spatial positions. For example, the

Kiruna (KIR) cluster contains 3544 events while the complete area shown in the figure contains 7793 events. The three main mines clusters together include [3544 (KIR) + 956 (KHI) + 325 (ZAP)] = 4825 events where KHI=Khibiny and ZAP = Zapolarny. Therefore, only 2968 events (38 %) lay outside these 3 clusters. Such cluster distributions can be 'sharpened' by computing first (gradient) and second (curvature) order spatial derivatives of event distributions as demonstrated in Fig. 2. As a supplement here individual mining operations in Khibiny are shown in Fig. 3. The Nansen (NKK) station near Kirovsk record many mining explosions which occasionally trigger avalanches in winter times. Let location ability of the NN algorithm be twice wider than the cluster shape and be expressed as a 2D Gaussian

$$A(x,y) = A_0 \exp\left\{-\frac{1}{2(1-r^2)}\left[\frac{(x-x_0)^2}{2\sigma_1^2} - 2r\frac{(x-x_0)(y-y_0)}{\sigma_1\sigma_2} + \frac{(y-y_0)^2}{2\sigma_2^2}\right]\right\}$$

with $\sigma_1 \approx \sigma_2 = 60$ km. The parameter A_0 is assumed to be 1, but may be smaller. The earthquake p.d.f. $p_q(x,y,t)$ is almost constant in time, $p_q(x,y,t) = p_q = 0.8 \cdot 10^{-6}$ km^{-2} year^{-1}; the last figure came from the "trend plane" (Fig. 4), where the plane surface was fitted to the remaining events after the clusters are removed. We can calculate the number of earthquakes N_{qpass} and explosions $N_{xpass} = N_{total} - N_{qpass}$ "passing through" the NN algorithm in unit time (here 1 year) as $N_{qpass} = \int_{\infty}^{\infty} A(x,y)p_q dxdy$. For example, taking the EQ p.d.f. for Kiruna as $p_q = 0.8 \cdot 10^{-6}$ year^{-1}km^{-2} which gives $N_{qpass} \approx 2 \cdot 10^{-2}$ year^{-1} for this cluster. Now we can calculate the probability of wrongly identifying an earthquake as an explosion at KIR. For mutually independent events Q and X, $Q \bigcap X = 0$ and $Q \bigcup X = 1$, where Q stands for "recorded event is an earthquake" and likewise X - "recorded event is an explosion", so we obtain

$$P(Q) = \frac{N_{qpass}}{N_{total}}.$$

For KIR $N_{total} = 3544$ year^{-1} which gives $P(Q) = 2 \cdot 10^{-2}/3544 = 5.6 \cdot 10^{-6}$. Such a probability of earthquake occurrence is almost negligible, hence we can use a simple decision rule: Take all events from this cluster to be explosions, the corresponding probability of error $P(Q) \approx 5.6 \cdot 10^{-4}\%$.

Further refinements are feasible using the distribution of explosions over time, say local time of day. Recall Bayes theorem for Q and X; $Q \bigcap X = 0$ and $Q \bigcup X = 1$, then

$$P(Q|B) = \frac{P(Q) \cdot P(B|Q)}{P(Q) \cdot P(B|Q) + P(X) \cdot P(B|X)}$$

B defines "event in specific time interval (in our case hour)" , $P(Q)$ and $P(X)$ as before the probability of an earthquake and explosion, respectively and $P(Q|B)$ - probability of an earthquake within a hour interval for a given day of week. Also $P(B|Q)$ - probability of an earthquake to occur at a specific hour is taken to be 1/24 assuming that the occurrence of earthquakes does not depend on time of day. Similarly, $P(B|X)$ is a probability of an explosion to occur in a given hour which is obtainable from the results given above. On this basis we calculate the probability to recognize earthquakes as explosions from the Kiruna cluster in the local hours 0-1 and 4-5. From the daily distribution (Fig. 1) we obtain

$$\begin{aligned} P(B|X)_{0-1} &= [1 - P(Q)]\frac{586}{3544} = 0.16535 \\ P(B|X)_{4-5} &= [1 - P(Q)]\frac{18}{3544} = 0.005079 \end{aligned}$$

Using Bayes formula we obtain eventually

$$\begin{aligned} P(Q|\text{event in } 0-1) &= \frac{5.6 \cdot 10^{-6} \cdot (1/24)}{5.6 \cdot 10^{-6} \cdot (1/24) + (1 - 5.6 \cdot 10^{-6}) \cdot 0.1635} = 1.43 \cdot 10^{-6} \\ P(Q|\text{event in } 4-5) &= \frac{5.6 \cdot 10^{-6} \cdot (1/24)}{5.6 \cdot 10^{-6} \cdot (1/24) + (1 - 5.6 \cdot 10^{-6}) \cdot 0.0050790} = 4.59 \cdot 10^{-5} \end{aligned}$$

As demonstrated above, exploiting the fine structure of daily event distribution we obtain improved error estimates. These results clearly implies that in N. Fennoscandia & Kola the CTBT source discrimination problem is mainly that of differentiating between numerous chemical (mining) explosion and nuclear explosions since the probability of earthquake occurrence is small indeed.

CLUSTER REMOVAL IN PRACTICE

In summary, the above cluster removal is simple:

- make 2D histogram of all events from bulletins for the area of interest;
- calculate slopes using spatial derivatives of histogram and its curvature (Laplacian);
- sort slopes and curvature in descending order;
- set percentage of area assumed to be under clusters, e.g. 20%;
- remove first 20% of cells in slopes and curvature sorted list;
- put smooth surface on the remaining cells providing an estimate of EQs p.d.f.;
- fit polynomial trend to the above surface.

This trend will be average estimate of earthquake p.d.f. over the area of study.

W. NORWAY EVENT DISTRIBUTION

A display in the form of event occurrence per unit area (km^2) and time (10 years = 01/01/90 - 31/12/99) is given in Fig. 5. As map inserts are shown time of day distributions for the 6 boxed areas having the highest event activities. Area 1 encloses the Titania mine which shooting practices are exceptionally time-space stationary. Practically all events take place in 2 subsequent hour intervals; two because semiannual changes between summer/winter times. Locally, this kind of knowledge is apparently non-existent since analyst continues to read P- and S-arrivals for every explosion. It will suffice to read just one P-arrival for origin time as epicenter is known to nearest kilometer. The Area 2 and 3 stem from road construction work (undersea tunnel) and harbor construction work, respectively. In the latter area, relatively many events are given non-zero focal depths in the bulletin listings. However, we do not consider these depth estimates as proof of events being earthquakes. In Area 4 (Bergen district) a large number of major construction works have taken place during the last decade including bridges, underground oil storages and major harbor works. Better spatial resolution should be obtainable using shorter time periods of say 2 years. Area 5 (off-shore) is obviously earthquake prone in view of the approximately flat hour-of-day distribution. Also, naval exercises do not involve use of WW 2 types of heavy depth charges any more so explosion sources at sea is very infrequent today. However, there are obviously some explosions within this population which we would attempt to identify in a subsequent study. Road construction works (undersea tunneling) account for almost all events in Area 6 in 1991/92.

Adapting the cluster analysis technique described above we proceeded as follows; firstly the basic assumption is that explosion events are clustered in the sense of steep curvatures and sharp gradients and hence are removed using a corresponding 0/1 spatial weighting. Note, any assumptions regarding flat/non-flat earthquake/explosion occurrence distributions as a function of time of day is not incorporated here. Then, a smooth surface is fitted to the residual presumably spatial earthquake distribution given a p.d.f. maximal value in the Area 5 $\sim$ $0.05\,\mathrm{km}^{-2}\,\mathrm{year}^{-1}$. The validity of this estimated can be tested on selected areas like Area 1 in Fig. 5; over the time interval of 10 years about 6 EQ (one every 4th hour) should have occurred in the Titania area but this is obviously not the case. Similar results are found for many smaller areas in particular east of longitude 5.0° East. On this basis we refined our analysis; in essence we found that off-shore areas are exclusively earthquakes while between 4 - 6 E and 58 - 63 N we have mixed populations while further east explosion events are dominant. In other words, the assumption of uniform EQ p.d.f. for the whole area (Fig. 5 map) is only valid as a first approximation. In the mentioned area with mixed EQ/explosion population, the open pit mine Titania (Area 1; Fig. 5) produce event waveforms which are easily recognized as such (Fedorenko et al, 1999). Spatial cluster analysis for W. Norway did not work too well here simply because the very spiky event distribution and relatively small number of events. For Kola such distributions are smoother due to the accumulation of several mines in a small area and also due to lesser accuracy in epicenter locations. For W. Norway we replaced the curvature and gradient mapping with a rather crude spatial event plot that is eliminating all events between 04 a.m. - 08 p.m. (retaining nocturnal events only) as shown in Fig. 6. In other words, EQ occurrence is confined to a narrow N/S-trending zone in the coastal areas and as mentioned those off-shore. Also, 15 felt EQs are reported for this area in the 1990/99 reporting period.

The really difficult events are underwater harbor works since explosions here could take place at any hour and sometimes preferably at night due to shipping traffic. Pure statistical means in assuming EQ only off-shore W. Norway and explosion only like in Kola would probably be better than actual discriminant analysis where error rates of a few per cent is common. However, in the area of mixed populations the tedious work of introducing waveform diagnostics would be needed. As student work, we will start to undertake discriminant analysis initially using the explosion signal recognition approach.

CONCLUSIONS AND RECOMMENDATIONS

Albeit some details remain in our studies of Norsar and University of Bergen event listings we have confidence in the following conclusions.

- Event populations in N. Fennoscandia and Kola (NW Russia) are completely dominated by mining explosion clusters in Kiruna, Khibiny and Zapolarny.
- A combination of trend and cluster analysis give that the p.d.f. of EQ occurrences in these mining areas is negligible so in a CTBT context the discriminant problem is confined to chemical versus nuclear explosions.
- Similar results are obtained for W. Norway although here off-shore areas are exclusively earthquakes. However, in coastal areas explosions dominate but EQ occurrences cannot be ignored.
- Our space-time cluster analysis is well suited for limiting explosion source areas and thereby identifying events which should be useful for more elaborated source discrimination studies using event waveforms and their corresponding envelope transforms.

Recommendations: The results obtained suggest that aseismic regions like Fennoscandia and NW Russia can be monitored in more efficient ways than presently done. Reason being that too few seismic stations are used so due epicenter inaccuracies spatial event plots exhibit similarities to seismicity mapping. By deploying many more inexpensive seismic stations more accurate event locations would be feasible and moreover explosion source signal recognition would be feasible as part of automated event processing. Fedorenko and Husebye (ibid) demonstrate that inexpensive 3-comp. geophones can be operated as a high quality seismograph station (cost less than US $ 1000) and besides local high schools appear to be enthusiastic about operating such stations.

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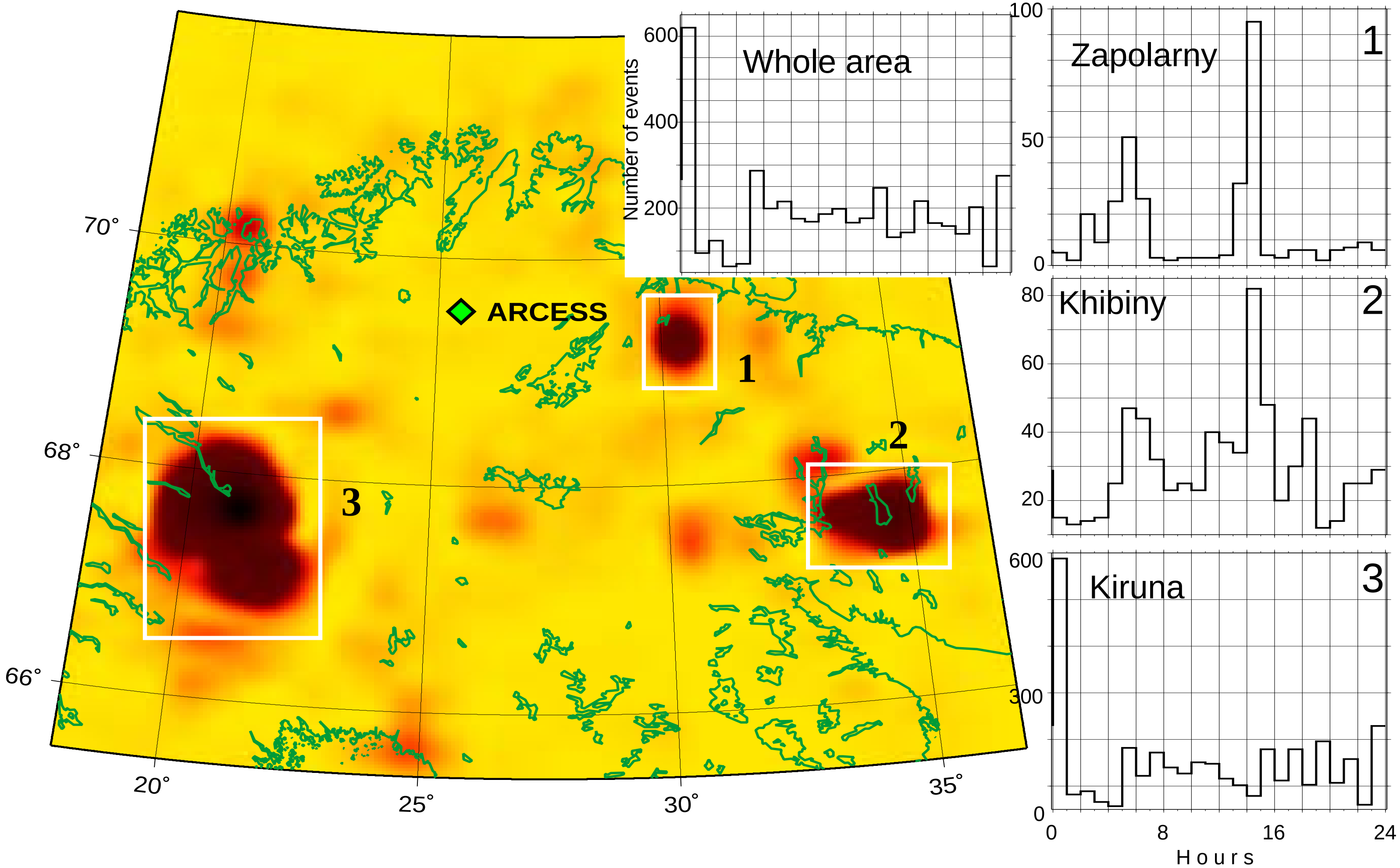

Fig. 1. Event distribution in Fennoscandia and NW Russia (Kola) as reported by Norsar through their bulletins for the time period Oct, 98 - Oct, 99 based on their generalized beamforming technique for automatic epicenter determinations.

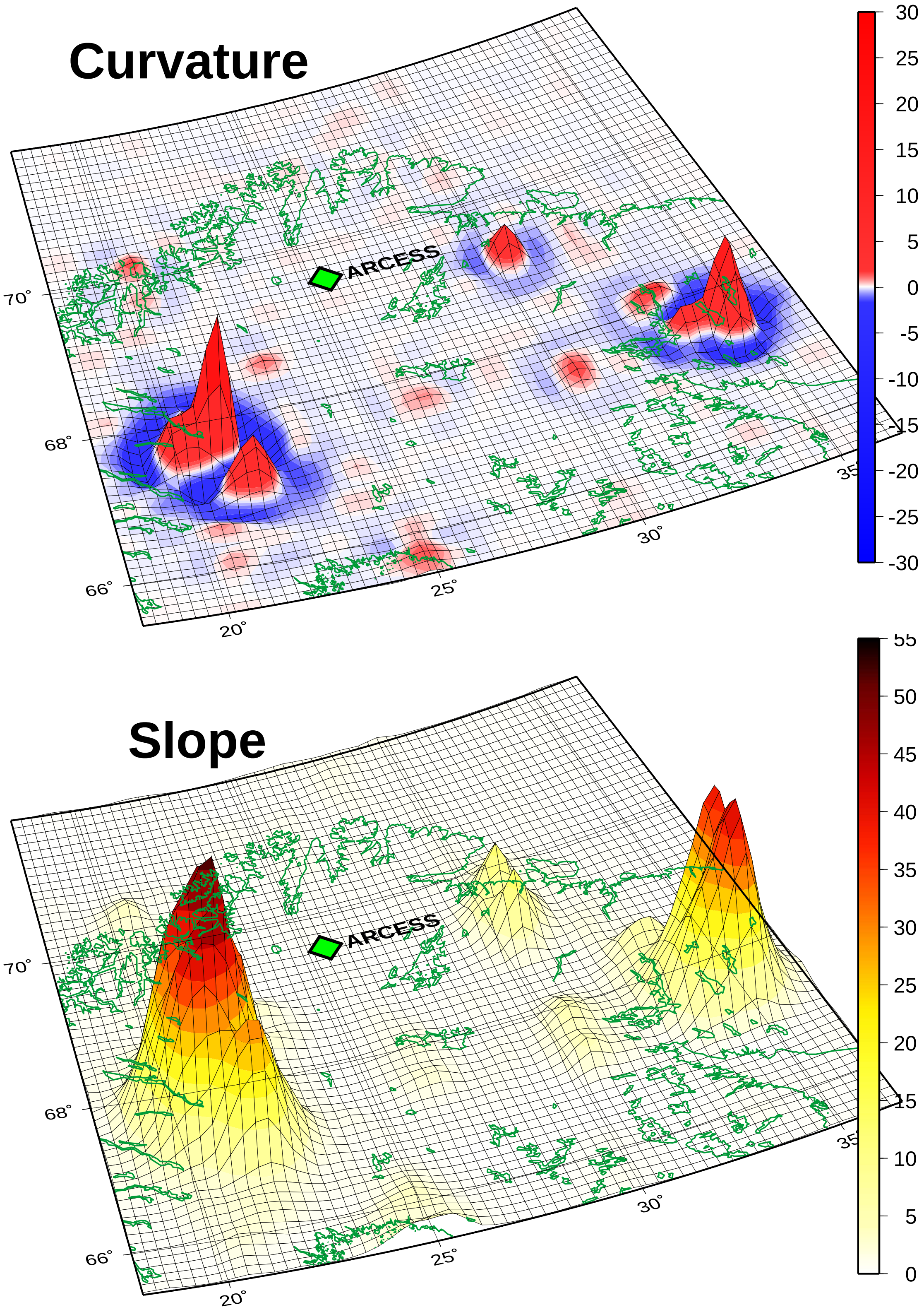

Fig. 2. First (gradient) and second (curvature) order spatial derivatives of event distributions.

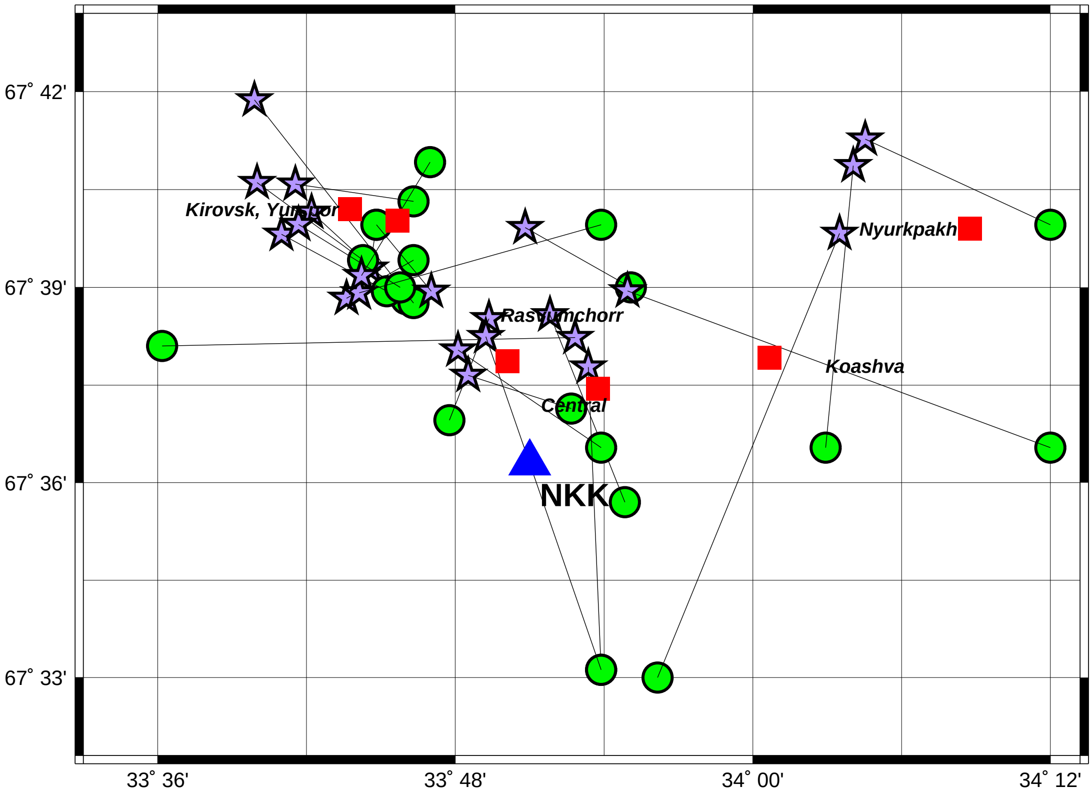

Fig. 3. Individual mining operations in Khibiny located by NKK seismic station. Sqares indicate active mines, stars and circles indicate epicenter locations by us and Kola Regional Seismological Centre respectively.

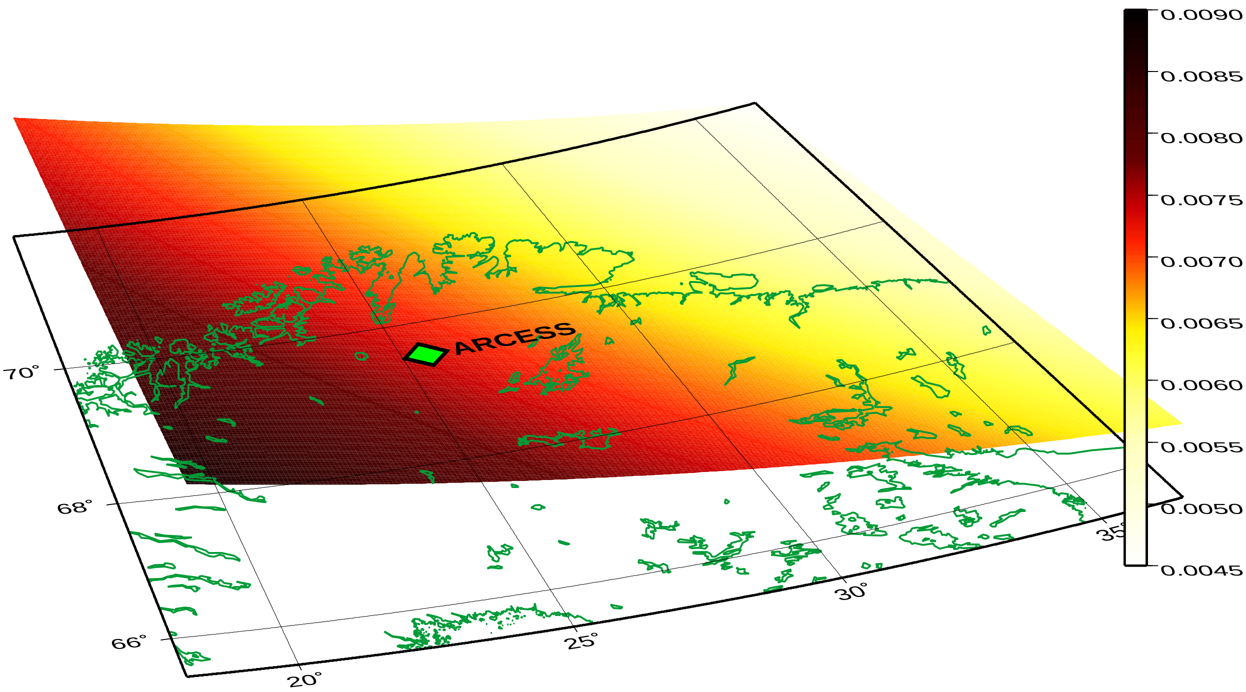

Fig. 4. Plane surface fitted to the remaining events p.d.f. after the clusters are removed; the probability of EQ occurence in this region is negligible.

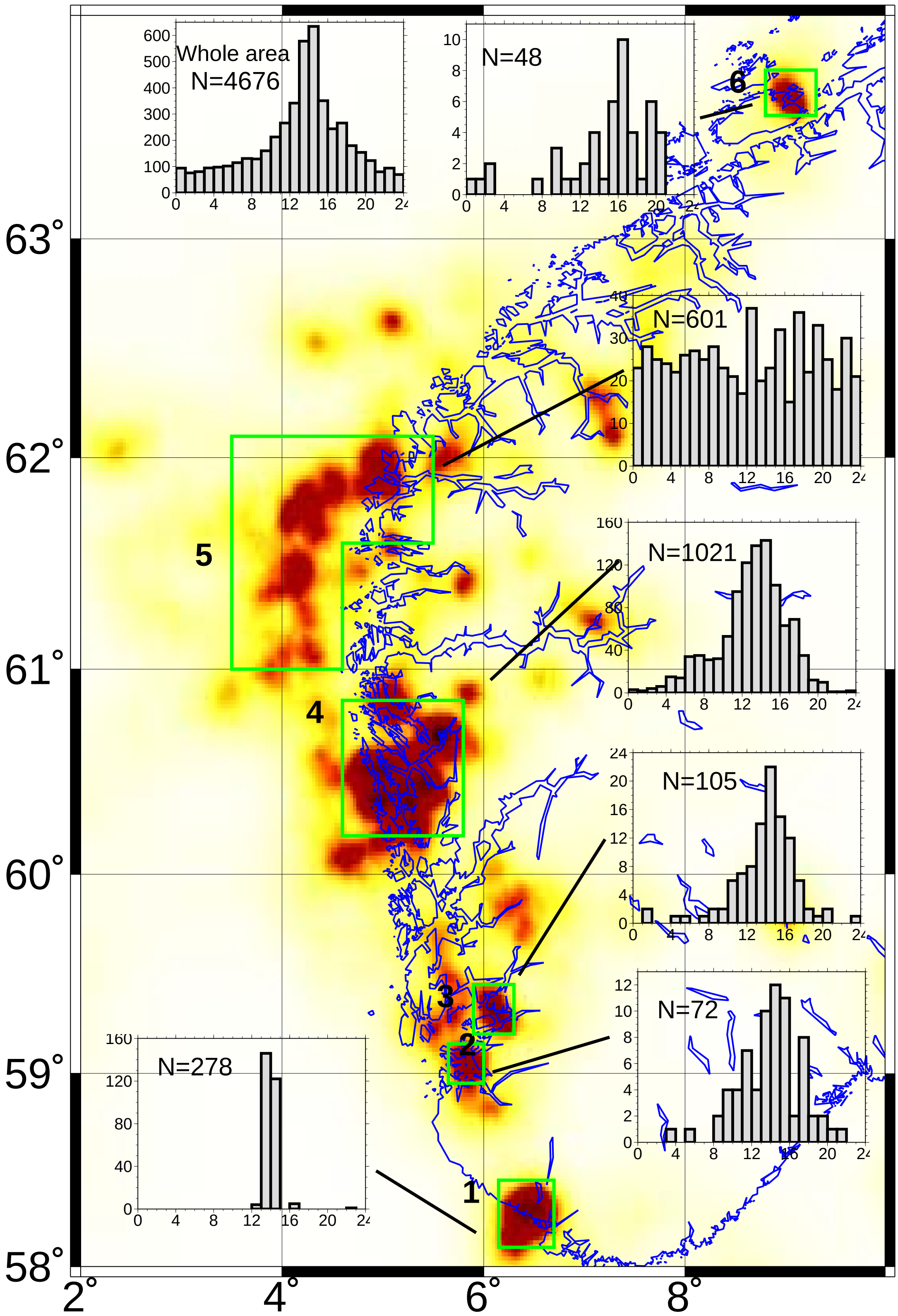

Fig. 5. The event distribution in W. Norway. The data used are 10 years of bulletin listings 01/01/90 - 31/12/99. For this area the epicenter locations are far more accurate due a relatively dense local network operated by the University of Bergen and analyst inspections of recordings.

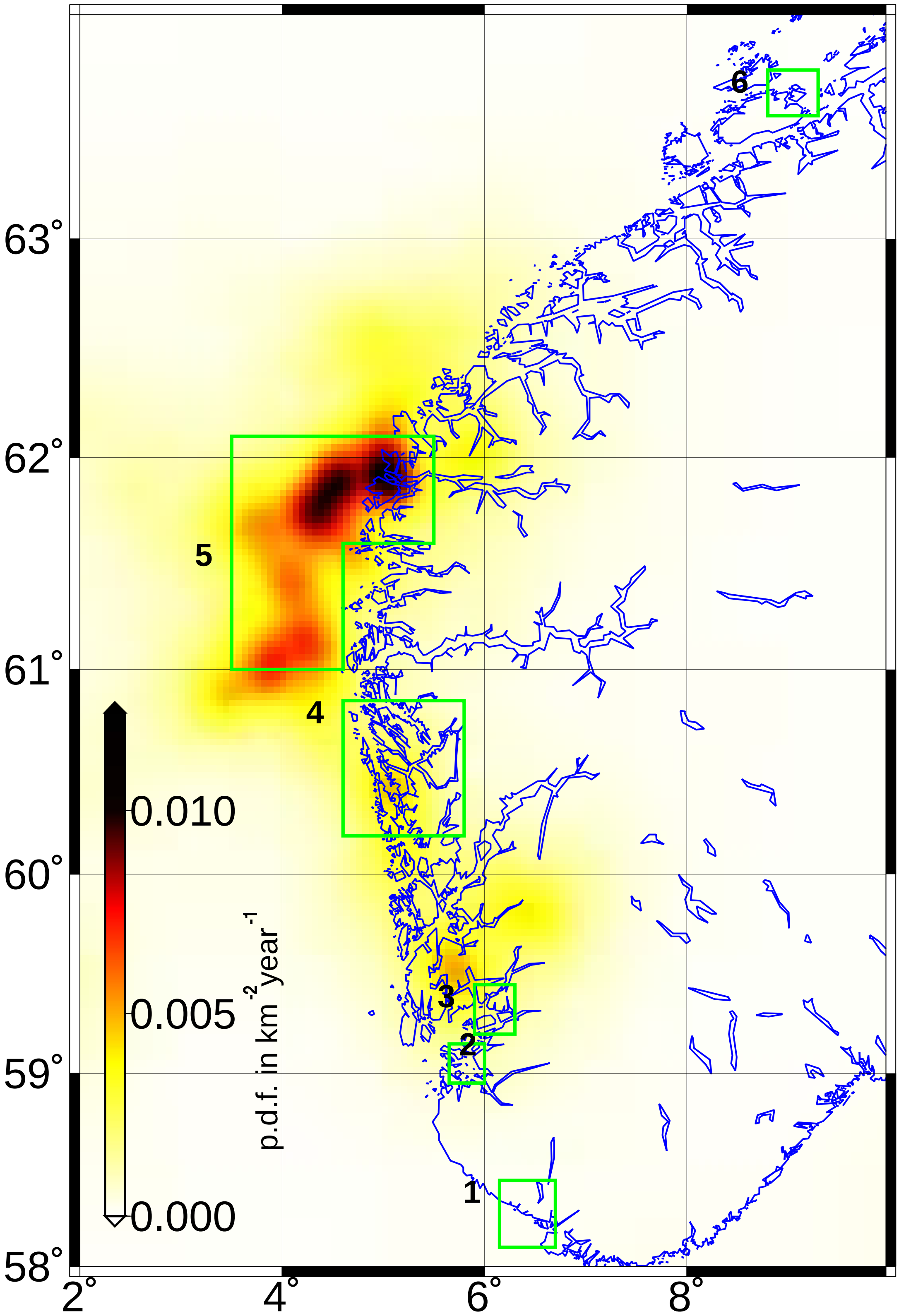

Fig. 6. Noctural (8 p.m. - 6 a.m.) event distribution for W. Norway outlining a narrow coastal seismicity zone from 59N/6E - 62N/4E.